S282 Astronomy

# Investigating supernova remnants

**Study time: 90 minutes**

## Summary

In this activity you will be using images of the remnants of four comparatively recent supernovae: Cassiopeia A (Cas A), the Crab, Kepler, and Tycho. You will investigate the supernova remnants (SNRs) at radio, optical and X-ray wavelengths, observe the similarities and differences, and use the on-screen ruler to measure the angular sizes of the SNRs and calculate their mean expansion speeds.

You should have read Sections 8.3 and 8.4 of *An Introduction to the Sun and Stars* before starting this activity.

## Learning outcomes

- Familiarity with the morphologies of supernova remnants at radio, optical and X-ray wavelengths.
- Calculate the radius of an astronomical body given its angular size and distance.
- Calculate the time-averaged expansion speed of a supernova remnant.
- Recognize that the time-averaged expansion speed of a supernova remnant is an overestimate of the current expansion speed.
- Understand that spatial resolution depends on the telescope used, and that some differences in appearance between images taken in different wavelength bands arise from differences in spatial resolution.

## Background to the activity

The supernova that gave rise to the Cassiopeia A SNR is thought to have exploded about 300 years ago, though there are no records of it being observed. In the activity you will find a possible explanation for why this supernova was not seen at the time.

The Crab, Tycho and Kepler SNRs are all remnants of supernovae that were observed when they exploded; the Crab by Chinese astronomers and Tycho and Kepler by the European astronomers whose names they now bear. The Crab supernova remnant is the most easily viewed supernova remnant in the sky – it can be seen using large binoculars or a small telescope.

Some basic data about the four SNRs that you will study in this activity are given in Table 1.

**Table 1** Supernova remnant data.

| | **Cas A** | **Crab** | **Tycho** | **Kepler** |
|---|---|---|---|---|
| year of supernova (AD) | about 1700 | 1054 | 1572 | 1604 |
| distance[1]/kpc | 3.4 | 1.9 | 2.4 | 5.0 |
| RA | 23 h 23 min 24 sec | 05 h 34 min 32 sec | 00 h 25 min 13 sec | 17 h 30 min 41 sec |
| Dec | +58°49′ | +22°01′ | +64°09′ | –21°29′ |
| constellation | Cassiopeia | Taurus | Cassiopeia | Ophiuchus |

[1]Note that the distances to supernova remnants are very difficult to determine with any certainty. For the purposes of this activity we will assume (rather simplistically) that all of the distances quoted here are known to an accuracy of ±20%.

# Part 1 Multiwavelength views of supernova remnants

You will be using optical, X-ray and radio images of the four supernova remnants in Table 1. The optical data are from the Digitized Sky Survey, which is sensitive to a wavelength range that is centred on $\lambda \approx 500$ nm. Note that these data are shown as photographic negatives – the sky is white and any sources of emission are grey or black. The X-ray data are from an instrument called the High Resolution Imager (HRI) on the ROSAT observatory – these maps are sensitive to photons with energies of about 1 keV (i.e. $10^3$ eV) or equivalently $\lambda \approx 1$ nm. The radio data are from a survey carried out by the Very Large Array (VLA) that is sensitive to radio waves with wavelengths $\lambda \approx 0.2$ m.

The year in which the observations were made are given in Table 2.

**Table 2** The dates of observation of the multiwavelength image set of supernova remnants.

| **Band** | **Year of survey** |
|---|---|
| optical | 1956, except Kepler SNR (1987) |
| X-ray | 1992 |
| Radio | 1995 |

All images are provided in the Image Archive.

- Start the S282 Multimedia guide and open the folder called ‘Stars’, then click on the icon for this activity (‘Investigating supernova remnants’).
- Press the Start button to launch the Image Archive at the required set of images.
- Alternatively, launch the Image Archive by clicking the Image Archive button in the Multimedia guide and then find the ‘Supernova Remnants – Multiwavelength images’ set which is located within the ‘Stars’ section of the archive.

Once you have opened the Image Archive at the page that displays the multiwavelength images of supernova remnants take a few moments to read the instructions of how to display the different images. You are now going to look at the images in each wavelength band (optical, X-ray and radio) for each supernova remnant in turn.

- Click on the button labelled Cas A SNR that is on the upper right-hand part of the screen.
- An optical image of the field of view that contains the Cassiopeia A supernova remnant should now be displayed. Don't be too concerned if you can't work out where the supernova remnant is! You are now going to look at the same field of view in the X-ray and radio parts of the electromagnetic spectrum.
- At the lower right-hand part of the screen you should see a table that has three columns that are headed Image, Contour and Contour. To start with, you are simply going to look at images at different wavelengths, and these are accessed by clicking on the relevant wavelength range in the Image column.
- Click on the term X-ray in the Image column. This will display an X-ray image of the supernova remnant. Note what you see and how it compares to the optical image.
- Now view the radio image by clicking on the term Radio in the Image column. A radio image of the supernova remnant will be displayed. Again, note how it compares to the optical image.

View the optical, X-ray, and radio images for each of the four supernova remnants in turn. As you do so, make notes of appearance of the supernova remnant at this waveband and attempt to answer the following questions.

## Question 1

(a) Is every supernova remnant visible in all three wavelength ranges (optical, X-ray and radio)?

(b) Which wavelength ranges would be best suited to searching for supernova remnants?

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In answering Question 1 you probably came to the conclusion that the optical images are not well suited to the detection of supernova remnants.

- Suggest a reason why not all supernova remnants are visible at optical wavelengths.

❑ The primary reason is due to the absorption of visible light by dust in the interstellar medium between us and the remnant.

This is most clearly seen in the case of the Cas A remnant. Some of the remnant is visible at optical wavelengths, but most appears to be missing. This suggests that something – interstellar dust – is obscuring the major part of the remnant. This also offers an explanation as to why the supernova that gave rise to Cas A was not seen – it was most probably obscured by the intervening interstellar medium.

## Question 2

Compare the X-ray images of all four supernova remnants with one another.

(a) Are any of the images similar, and if so, in what way are they similar? What does the appearance of these remnants suggest about their structure?

(b) One of the supernova remnants is distinctively different to the other three. Identify this remnant and describe in what way it looks different.

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You are now going to compare emission at two different wavelengths. A common technique in astronomy is to show emission at two different wavelengths by overlaying an image at one wavelength with a contour map that corresponds to the other wavelengths. To start with, however, you will see how a contour map relates to one of the images that you have already viewed.

- For the Cas A supernova remnant view the X-ray image by clicking on the term X-ray in the Image column.
- Now display the X-ray image with X-ray contours by clicking on X-ray in the same row of the table as before but now in the column marked Contour.

You should be able to see that the contours simply follow the intensity of the X-ray emission from the supernova remnant. Just as contours on a map indicate the topography with lines of equal height, these contours show lines of equal surface brightness. Now you are going to compare the X-ray emission with the optical image of the remnant.

- In the row of the table that starts with the term Optical, click on the term X-ray that occurs in the Contour column. You should see the optical image with the X-ray contours overlaid.

## Question 3

Is there any correspondence between the optical and X-ray emission of the Cas A supernova remnant?

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Now that you have seen one combination of an image with a contour overlay try other combinations and for different SNRs. When you have understood how to show any combination of image and contours that is available, attempt the following question.

## Question 4

Compare the X-ray emission with the radio emission for all four supernova remnants. For each case describe whether the X-ray emission and the radio emission seem to arise from the same parts of the supernova remnant. Also make a note of any general differences between the images in these two wavelength bands.

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In answering Question 4 you may have noticed that the radio emission appears to be more smoothly distributed than the X-ray emission, and that it appears to have a greater extent.

- ■ Give two possible reasons for the radio emission appearing to be more smoothly distributed than the X-ray emission.
- ❑ One cause of this difference may be that the radio and X-ray emitting regions are genuinely different and distributed as shown.

  Another cause of this difference may be that the spatial resolution of the X-ray image is different to that of the radio map. It could be that both the X-ray and radio emitting gas are distributed in the same way, but that radio images are more 'blurred' because the spatial resolution is lower.

In fact, there is a substantial difference between the spatial resolution of the images at different wavelengths. The X-ray images have a spatial resolution of about 7 arcsec, whereas the radio maps have a spatial resolution of 45 arcsec. Any features in an image that have an extent that is less than the resolution of that image will become spread out and appear about the same size as the spatial resolution. One important implication of using a low-resolution map to study a supernova remnant is that this 'blurring' will make the remnant appear more spread out than it really is.

Thus the most likely reason for the radio emission appearing to be more smoothly distributed and spread out than the X-ray emission is due to the different spatial resolution of the maps in these two wavelength bands. In fact, higher resolution radio maps confirm this view.

It should be noted that radio maps can be made over a wide range of resolutions that depend on the way in which a radio telescope (or a group of radio telescopes) is used. You may see examples of radio maps that have resolutions ranging from a few milli-arcseconds up to a few degrees – depending on the instruments and techniques adopted. The radio data shown here are from a survey of the sky that was carried out at a fairly low spatial resolution.

# Part 2 Measuring the time-averaged expansion speeds of supernova remnants

In this part of the activity you will measure the mean speed of expansion of each supernova remnant by measuring how far the outer edge of the remnant has travelled since the time of the initial explosion. This will involve measuring the angular size of each remnant and then calculating their radii. However, the first task is to decide what images you are going to use for your measurements, and this is the subject of the next question.

## Question 5

What criteria are important in deciding which wavelength band (optical, X-ray or radio) should be used for determining the angular size of the supernova remnants? Which wavelength band (optical, X-ray or radio) should be used to determine the angular sizes of each of the remnants?

In answering Question 5 you should have concluded that in the case of the Crab it is the optical image that should be used to determine the angular extent of the remnant. For the other three supernova remnants it is the X-ray images that should be used for this measurement.

It should be noted however that there is an inherent danger in using different wavelength ranges to measure what you assume to be the same type of feature in different astronomical objects. It may be that the features at different wavelengths are profoundly different in some way, and could lead to quite erroneous conclusions. Having said that, we shall carry on with the analysis on the basis described above, but you should keep in mind that the Crab supernova remnant is being measured in a different way to the others.

## Measuring the angular diameter

- Select the Tycho SNR and look at the X-ray image overlaid with the X-ray contours.

This provides a good picture of the expanding spherical shell of material. The shock wave is travelling so fast that the surrounding interstellar medium (ISM) has no warning of what is about to hit it. The outermost contour gives a reasonable estimate of the position of the shock front.

To help you to measure the angular diameter of these images the Image Archive includes a screen ruler. This is a tool that gives the angular distance in arc minutes between any two positions on the image. The ruler is used as follows:

- Place the cursor on the left-hand limb of the remnant. Now, while holding down the left mouse button, drag the cursor from this position across the image to the right-hand limb. As you do so you should see a line stretch out between the position that you started from and the current cursor position. Release the mouse button when you have positioned the cursor on the right-hand limb.

In addition to the line between the two points you should also see a white panel that gives the length of the line in terms of the pixels of the image and the angular distance covered by the line in units of arcmin. It is the angular distance given in arcmin that we shall use for our measurements here. (This information is also given at the top of the screen, just beneath the title.)

- Try measuring the diameter of the supernova remnant in several different directions (left to right, top to bottom, etc.). Record your measurements and estimate the angular diameter $\alpha$ of the remnant. Insert this value of $\alpha$ – expressed to an appropriate number of significant figures – into Table 3. Note: the next few sections take you through the process of completing Table 3.

## Question 6

(a) By using several measurements, obtain a value for the diameter of the supernova remnant.

(b) Try to make a (rough) estimate of the uncertainty in this measurement. Hence quote the mean angular diameter of the supernova remnant with its associated uncertainty.

(c) Express the estimated uncertainty as a relative uncertainty.

(d) What is the origin of the uncertainty?

**Table 3** Table of results for determining the time-averaged expansion speeds of supernovae.

| | Cas A | Crab | Tycho | Kepler |
|---|---|---|---|---|
| Wavelength band used for measurement of angular diameter | | | | |
| Angular diameter $\alpha$ /arcmin (from your measurements) | | | | |
| Angular radius ($\alpha$ /2)/radians | | | | |
| Distance $d$/pc (from Table 1) | | | | |
| Radius $R$/pc | | | | |
| Radius $R$/km | | | | |
| Date of supernova explosion (from Table 1) | | | | |
| Date of observation (from Table 2) | | | | |
| Time since explosion $t$/s | | | | |
| Time-averaged expansion speed and associated uncertainty $v$/km $s^{-1}$ | | | | |

## Finding the radius of the supernova remnant

We use the same approach as in *An Introduction to the Sun and Stars* Section 3.3.1 for measuring the radius of a star:

$$R = [(\alpha /2)/\text{radians}] \times d$$

(*An Introduction to the Sun and Stars* Equation 3.8)

where $d$ is the distance to the SNR, $\alpha$ is its angular diameter (so $\alpha$ /2 is its angular radius), and $R$ is its radius in the same units as $d$. Note that the angle must be expressed in radians rather than in arcmins.

There are two measured quantities, $\alpha$ and $d$, in the above equation, and both of these quantities have associated uncertainties. Strictly speaking the uncertainty in $R$ should be calculated by combining the uncertainties in both $\alpha$ and $d$. However, in your answer to Question 6 you should have found that the relative uncertainty in $\alpha$ is only a few per cent, whereas the relative uncertainty in $d$ is about 20% (see the footnote to Table 1). It is the uncertainty in $d$ that is the most important factor in determining the uncertainty in $R$. In fact, it is reasonable to assume that the relative uncertainty in $R$ is the same as the relative uncertainty in $d$, i.e. the calculated radius will also have an uncertainty of ±20%.

### Question 7

Using the angular radius that you have just measured for the Tycho supernova remnant and data from Table 1, calculate the radius $R$ of the supernova. Express this radius in parsecs and km. Also calculate the uncertainty in the calculated radius. Enter your results in Table 3.

(You may assume 1 arcmin = $2.91 \times 10^{-4}$ radians, and 1 parsec = $3.09 \times 10^{13}$ km.)

## Determining the time-averaged expansion speed

The time-averaged expansion speed of the shock front can be found by dividing the radius $R$ of the remnant by its age $t$

$$v = R/t$$

As far as the uncertainty in $v$ is concerned, it can be assumed to be the same as the relative uncertainty in $R$, i.e. ±20%. (This is because the relative uncertainty in the time elapsed between the supernova explosion and the date of the observation is small in comparison to the relative uncertainty in $R$.)

### Question 8

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Calculate the time-averaged speed of expansion of the Tycho SNR in km $s^{-1}$. Express this value and its uncertainty to an appropriate number of significant figures.

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## Comparing the time-averaged expansion speeds of supernova remnants

The final part of the activity involves calculating the time-averaged expansion speeds of the other three supernova remnants (Cas A, Crab and Kepler).

### Question 9

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(a) Determine the mean expansion speeds for the other three SNRs in the same way and complete Table 3. (You may want to write a spreadsheet to perform these calculations.) Note that rather than repeating the uncertainty calculations it is sufficient to assume that the relative uncertainty of all of the calculated time-averaged expansion speeds is ±20%.

(b) How do the expansion speeds compare with one another?

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As a result of your calculations you should have found that the time-averaged expansion speeds of these supernova remnants lie in a range of between about $1 \times 10^3$ and $8 \times 10^3$ km $s^{-1}$. Even by astronomical standards these are high speeds, and are an indication of the vast amount of energy that was released in the initial supernova explosion. You should also have noticed that the time-averaged expansion speed of the Crab remnant is significantly lower than the expansion speeds of the other three remnants.

We end this activity by considering whether this difference in expansion speeds is a real effect and, if so, whether it has a straightforward explanation.

■ Is there any difference in the method you used to determine the expansion speeds between the Crab remnant and the other three remnants?

❑ Yes. The expansion speed of the Crab remnant was measured from the optical image, whereas the expansion speeds of the other three remnants were determined from X-ray images.

This type of problem can be addressed by measuring the expansion speed of the Crab at X-ray wavelengths. A quick inspection of the X-ray image shows that the Crab remnant appears smaller in the X-ray images than it does in the optical – so this would imply an expansion speed that is even smaller than the value we calculated from the optical image. So it appears that this is a real effect and not one that has arisen from the way in which we have analysed the data.

### Question 10

Do you think the speeds you have found are the current expansion speeds? Justify your answer.

You might think that the low expansion speed of the Crab remnant is due to its age – it is over twice the age of the other remnants in our sample. However, detailed analysis shows that this is not the case: even when age is accounted for, the Crab remnant appears to be expanding at an anomalously slow rate. This implies that the supernova that gave rise to the Crab remnant probably released less energy than is typical.

You have already noticed that the Crab remnant looks quite different to other supernova remnants, but the reasons for this and for its slow expansion rate are a mystery. So the most famous and most easily visible supernova remnant is, ironically, one of the least understood.

## Answers to questions

### Question 1

(a) Table 4 provides a summary of whether individual supernova remnants can be seen at different wavelengths. It can be seen that these supernova remnants are not all visible at radio wavelengths, whereas all are visible at optical and X-ray wavelengths.

**Table 4** The visibility of supernova remnants at different wavelengths.

| | Cas A | Crab | Tycho | Kepler |
|---|---|---|---|---|
| Optical | partly visible | yes – clearly visible | no | no |
| X-ray | yes | yes | yes | yes |
| Radio | yes | yes | yes | yes |

(b) On the basis of these images it would seem that searches for supernova remnants would best be conducted in the radio or X-ray parts of the spectrum.

### Question 2

The X-ray images of the Tycho, Kepler and Cas A supernova remnants all have a similar appearance. These three images show emission from roughly circular region, and this emission is concentrated towards the circumference of the circle. The fact that all three of these SNRs look circular from Earth is an indication that the general morphology is close to spherical – it is unlikely that we would be at

just the right angle to see each of them as a circle otherwise. Furthermore the appearance of each image also seems to suggest that emission comes from a roughly spherical shell – towards the edge of the remnant we look though a greater depth of this shell and this gives rise to the bright edges.

The X-ray image of the Crab supernova remnant is quite different to the other three. In this case there is a very bright region of X-ray emission towards the centre of the remnant. There is no obvious ‘shell’ appearance to the remnant.

(Comment: a distinctive feature of the Crab is the presence of a pulsar near the centre of the remnant. It is thought that this pulsar is an energy source to its environment and causes the bright regions of X-ray and radio emission that are seen here. Pulsars are considered in more detail in Chapter 9 of *An Introduction to the Sun and Stars*.)

## Question 3

There is some optical emission that corresponds to the uppermost part of the remnant as viewed in X-rays. However, other parts of the supernova remnant that are bright in X-rays are not visible in the optical image.

This arises primarily because there are differing amounts of interstellar dust along different lines of sight to the remnant. Thus, in at optical wavelengths, the uppermost part of the remnant suffers from less absorption than the rest of the remnant.

## Question 4

The X-ray and radio emission can be compared by examining either the X-ray image with radio contours or the radio image with X-ray contours (or both). The similarities and differences between the emission in these wavelength bands are:

#### Cas A, Kepler and Tycho SNRs

1 The roughly spherical shell of emission is visible in both radio and X-rays.

2 The locations that show the most intense X-ray emission do not correspond to the regions that show the brightest radio emission.

3 The distribution of the radio emission appears smoother than that of the X-ray emission, and appears to have a greater extent.

#### Crab SNR

1 The radio and X-ray emissions appear to be quite different in extent. (The radio emission follows the optical emission quite well, but the X-ray emission is much more centrally concentrated.)

2 There is a bright spot of emission in both the X-ray and the radio emission – these are in roughly, but not exactly, the same location.

3 As is the case for the other three remnants, the distribution of the radio emission appears smoother and appears to have a greater extent than does that of the X-ray emission.

(Comment: the point about the radio emission appearing to be more smoothly distributed than the X-ray emission is taken up in the text immediately following Question 4 on pp. 4–5.)

## Question 5

The most important criterion is that the remnant should be clearly visible! Thus observations at optical wavelengths are ruled out for Kepler, Tycho and Cas A, and either radio or X-ray images should be used for measuring the diameter of these remnants. On this basis, any of the three wavelength bands could be used for measuring the angular extent of the Crab supernova remnant.

A second criterion, that was hinted at the end of Part 1, is that we should use the highest resolution images available. This will allow the edge of the remnant to be accurately located. In the case of the Crab remnant it is the optical image that provides the highest resolution and so this is the image that should be analysed. In the other three remnants we have already seen that there is a choice between using radio and X-ray images. However, in the notes it is stated that the X-ray images are at higher resolution than the radio images, and so it is the X-ray images that should be used.

## Question 6

(a) I measured the diameter of the supernova remnant in four directions and obtained the following values:

| **Direction** | **Angular diameter/arcmin** |
|---|---|
| vertical | 8.1 |
| horizontal | 8.0 |
| diagonal – upper left to lower right | 8.2 |
| diagonal – upper left to lower right | 7.5 |

The mean value of the angular diameter is then

$\alpha = (8.1 + 8.0 + 8.2 + 7.5)/4$ arcmin $= 7.95$ arcmin

(b) The four measured values differ by a few tenths of an arc minute in each case, so a reasonable rough estimate of the uncertainty would be between about 0.2 and 0.5 arcmin. Here we will use a value of 0.3 arcmin.

The mean angular diameter with associated uncertainty is then $\alpha = (8.0 \pm 0.3)$ arcmin

(c) The relative uncertainty is

$\Delta\alpha/\alpha \approx 0.3/7.95 = 0.038$

So the relative uncertainty in the measurement of the diameter of the supernova remnant is about 4%. (If you obtained a value of between 2% and 6% that would be a reasonable estimate.)

(d) The source of this uncertainty is not in the operation of the ruler but in the fact that the remnant is not perfectly spherical!

## Question 7

The angular diameter I measured (see the answer to Question 6(b)) for the Tycho supernova remnant was 8.0 arcmin. The first step is to convert this into an angle in radians

$\alpha = 8.0$ arcmin $= 8.0 \times 2.91 \times 10^{-4}$ rad $= 2.33 \times 10^{-3}$ rad

The radius of the remnant is found using

$R = [(\alpha/2)/\text{radians}] \times d$

(*An Introduction to the Sun and Stars* Equation 3.8)

In this case $d = 2.4$ kpc $= 2.4 \times 10^3$ pc (from Table 1), so

$R = (2.33 \times 10^{-3}/2) \times 2.4 \times 10^3$ pc

$R = 2.79$ pc

Expressed in terms of km this is

$R = 2.79 \times 3.09 \times 10^{13}$ km $= 8.63 \times 10^{13}$ km

As stated in the text, the relative uncertainty in $R$ is the same as the relative uncertainty in $d$.

$\Delta R/R = 0.20$

$\Delta R = 0.20 \times R = 0.6$ pc $= 1.7 \times 10^{13}$ km

So the radius of the supernova remnant is

$R = (2.8 \pm 0.6)$ pc $= (8.6 \pm 1.7) \times 10^{13}$ km

## Question 8

To calculate the time-averaged expansion speed it is necessary to know the radius of the supernova remnant and the time elapsed between the supernova explosion and the observation.

From Question 7 the radius is

$R = (8.6 \pm 1.7) \times 10^{13}$ km

The time elapsed between the year of the Tycho supernova explosion (1572, see Table 1) and the date of the X-ray observation (1992, see Table 2) is

$t = (1992 - 1572) \times 365 \times 24 \times 60 \times 60\ \text{s} = 1.32 \times 10^{10}\ \text{s}$

The time-averaged expansion speed is

$\upsilon = R/t = (8.6 \times 10^{13})\ \text{km}/(1.32 \times 10^{10})\ \text{s}$

$= 6.52 \times 10^3\ \text{km s}^{-1}$

The relative uncertainty in this value is ±20%, so

$\Delta\upsilon = 0.20 \times 6.52 \times 10^3\ \text{km s}^{-1}$

$= 1.30 \times 10^3\ \text{km s}^{-1}$

So the final result is that time-averaged expansion speed as measured from the X-ray image is

$\upsilon = (6.5 \pm 1.3) \times 10^3\ \text{km s}^{-1}$

## Question 9

(a) The method for calculating the time-averaged expansion speeds of the other remnants is the same for Tycho. The only problem of note is that the Crab remnant is clearly not circular, but an estimate of the mean diameter can still be made by measuring the remnant along its long and short axes.

Table 5 shows one set of results and calculations. Note that the intermediate values used in calculating the final result are quoted to one significant figure more than is justified by the data – this is to reduce rounding errors in the intermediate calculations. Also note that your values may differ from those given here, but you should arrive at values of the time-averaged expansion speed that are consistent with those quoted here.

**Table 5** A completed table of results on the time-averaged expansion speed of supernova remnants.

| | **Cas A** | **Crab** | **Tycho** | **Kepler** |
|---|---|---|---|---|
| Wavelength band used for measurement of angular diameter | X-ray | optical | X-ray | X-ray |
| Angular diameter $\alpha$ /arcmin (from your measurements) | 4.7 | 4.3 | 8.0 | 3.5 |
| Angular radius ($\alpha$ /2)/radians | $6.84 \times 10^{-4}$ | $6.26 \times 10^{-4}$ | $1.16 \times 10^{-4}$ | $5.09 \times 10^{-4}$ |
| Distance *d*/kpc (from Table 1) | 3.4 | 1.9 | 2.4 | 5.0 |
| Radius *R*/pc | 2.33 | 1.25 | 2.79 | 2.55 |
| Radius *R*/km | $7.18 \times 10^{13}$ | $3.87 \times 10^{13}$ | $8.63 \times 10^{13}$ | $7.87 \times 10^{13}$ |
| Date of supernova explosion (from Table 1) | about 1700 | 1054 | 1572 | 1604 |
| Date of observation (from Table 2) | 1992 | 1956 | 1992 | 1992 |
| Time since explosion *t*/s | $9.21 \times 10^{9}$ | $2.84 \times 10^{10}$ | $1.32 \times 10^{10}$ | $1.22 \times 10^{10}$ |
| Time-averaged expansion speed and associated uncertainty $\upsilon$/km s$^{-1}$ | $(7.8 \pm 1.6) \times 10^{3}$ | $(1.4 \pm 0.3) \times 10^{3}$ | $(6.5 \pm 1.3) \times 10^{3}$ | $(6.4 \pm 1.3) \times 10^{3}$ |

(b) From Table 5 is can be seen that Cas A, Tycho and Kepler all have similar mean expansion speeds of between $6 \times 10^{3}$ and $8 \times 10^{3}$ km s$^{-1}$, whereas the expansion speed of the Crab is less than $2 \times 10^{3}$ km s$^{-1}$.

## Question 10

As the SNR expands it slowly begins to cool by radiating energy away, and it also sweeps up additional material from the surrounding interstellar medium, so the kinetic energy of the individual particles decreases. This means that the speed will gradually decrease, so the current speed will be less than the mean speed since the explosion.